

Long-Term Effects of Poultry Litter, Alum-Treated Litter, and Ammonium Nitrate on Phosphorus Availability in Soils

P. A. Moore, Jr.* and D. R. Edwards

ABSTRACT

Alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}$) additions to poultry litter result in lower ammonia (NH_3) volatilization and phosphorus (P) runoff; however, the long-term effects of alum on soil P behavior have been unknown. The objectives of this study were to evaluate the long-term effects of poultry litter, alum-treated litter, and ammonium nitrate (NH_4NO_3) on P availability in soils and P runoff. Two studies were initiated in 1995: a small plot (1.5×3.0 m) study and a paired watershed (0.405 ha) study. In the small plot study 13 treatments (control, four rates of normal litter, four rates of alum-treated litter, and four rates of NH_4NO_3) were applied to tall fescue (*Festuca arundinacea* Schreb.) plots. Results show that after 7 yr water-extractable P (WEP) in surface soil samples was greater with normal litter, but Mehlich III P was greater in surface soils fertilized with alum-treated litter. When soil samples were taken at depth intervals to 50 cm in Year 7, Mehlich III P was only greater in the surface 5 cm for soils fertilized with alum-treated litter. At lower depths Mehlich III P was greater with normal litter, and WEP was up to 288% greater when normal litter was used, indicating that alum significantly reduced P leaching. Uptake of P by fescue was not affected by alum. Results from the paired watershed study showed P loss in runoff was 340% greater for normal litter than for alum-treated litter. This research, combined with earlier work that shows alum use improves air and soil quality, supports the use of alum as a long-term solution to reducing P runoff and leaching.

IN FRESHWATER SYSTEMS, such as lakes and rivers, P is normally the element that limits eutrophication (Schindler, 1977). When excessive P loading occurs, large algal blooms can occur, resulting in degradation of water quality. Phosphorus concentrations in runoff water can be very high following poultry litter applications (Edwards and Daniel, 1992a, 1992b). In pastures, the majority of P in runoff water is in the water-soluble form (Edwards and Daniel, 1993; DeLaune et al., 2004a). This accelerates the eutrophication process, since water-soluble P (hereafter referred to as “soluble P”) is the most readily available form for algal uptake (Sonzogni et al., 1982).

Moore and Miller (1994) demonstrated that soluble P concentrations in poultry litter could be reduced with additions of compounds containing aluminum (Al), calcium (Ca), and iron (Fe) to litter. They also hypothesized that reducing soluble P in manure would reduce P runoff from fields fertilized with manure. Shreve et al.

(1995) found that additions of compounds such as alum reduced P runoff from small plots fertilized with broiler litter by 87%. Nitrogen uptake and tall fescue yields also were found to be greater with alum-treated litter than normal litter, which led Shreve et al. (1995) to hypothesize that additions of alum to the litter may have resulted in less N loss via NH_3 volatilization. This was borne out by Moore et al. (1995, 1996) who found that alum additions to poultry litter could reduce NH_3 emissions from litter by up to 99% in laboratory studies.

High levels of NH_3 in poultry barns have been known to cause problems with poultry production for several decades, including susceptibility to viral diseases (Anderson et al., 1964), reduced growth rates (Charles and Payne, 1966; Quarles and Kling, 1974), reduced feed efficiency (Caveny et al., 1981), decreased egg production (Deaton et al., 1984), and blindness (Bullis et al., 1950; Faddoul and Ringrose, 1950). Carlile (1984) suggested that NH_3 levels in poultry houses not exceed 25 ppm, due to the production problems mentioned above.

Moore et al. (1995, 1996) tested the most common amendments used for this purpose and found that alum and phosphoric acid were the most effective compounds. Alum additions to poultry litter reduce litter pH, which shifts the $\text{NH}_3/\text{NH}_4^+$ equilibrium toward NH_4^+ , which is not volatile. Subsequent work conducted in commercial broiler houses showed that broilers grown on litter treated with alum were heavier, had better feed conversion, lower mortality, and lower condemnations (Moore et al., 1999, 2000). In addition, propane use was significantly lower in houses treated with alum because ventilation (to remove NH_3) was lower. Because of its production benefits, alum is routinely used by the poultry industry; over 700 million chickens were grown with alum in the U.S. last year alone.

Several other benefits of treating poultry litter with alum have been noted over the past few years. Alum additions to litter have been shown to greatly reduce pathogens responsible for foodborne illnesses. Line (2002) found both *Campylobacter* and *Salmonella* numbers in litter and on bird carcasses were either greatly reduced or, with *Campylobacter*, totally eliminated with alum (pH reduction creates an unfavorable environment in the litter for these organisms). Heavy metal and estrogen runoff from fields fertilized with poultry litter has also shown to be significantly lower when the litter has been treated with alum (Nichols et al., 1997; Moore et al., 1998).

Gilmour et al. (2004) indicated that alum additions to poultry litter had no effect on poultry litter decomposition in soils, except that N mineralization may be greater. In a long-term study, Moore and Edwards (2005) showed that forage yields were 6% greater with alum-treated litter than with normal litter and 16% greater than with

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ammonium nitrate. The greater yields with alum-treated litter were attributed to the greater N in alum-treated litter than in normal litter, due to less NH_3 loss. In that study ammonium nitrate resulted in soil acidification after about 3 yr. By Year 7, the soil in plots fertilized with ammonium nitrate had exchangeable Al levels over 100 mg kg^{-1} . In contrast, the soil pH increased with alum-treated or normal poultry litter. These increases in pH resulted in lower levels of exchangeable Al in plots fertilized with either litter type than in the unfertilized control. Aluminum uptake by fescue and Al runoff were not affected by fertilizer treatment. Moore and Edwards (2005) concluded that poultry litter, particularly alum-treated litter, may be a more sustainable fertilizer than ammonium nitrate.

Sims and Luka-McCafferty (2002) validated earlier findings by Moore and coworkers that showed alum additions to litter reduce the solubility of P and heavy metals (As, Cu, and Zn) in litter. However, they suggested that there was a need to evaluate the long-term effects of using alum-treated litter on Al availability and P leaching and runoff. Moore and Edwards (2005) clearly showed that alum does not affect Al availability in soils, Al uptake by plants, and/or Al runoff. The objectives of this study were to compare the long-term effects of normal poultry litter, alum-treated litter, and ammonium nitrate (NH_4NO_3) on P availability in soils and P runoff. Two long-term studies were initiated in 1995 (small plot and paired watershed study) to meet these objectives.

MATERIALS AND METHODS

Small Plot Study

A small plot study utilizing 52 plots ($1.52 \times 3.05 \text{ m}$, with 5% slope) located at the Main Agricultural Experiment Station of the University of Arkansas on a Captina silt loam soil (fine-silty, siliceous, mesic Typic Fragiudult) was initiated in April 1995. All of the plots have runoff collection troughs at the downslope end which enables the collection of runoff water, and are hydrologically isolated with metal strips. Thirteen treatments were evaluated; four rates of alum-treated poultry litter, four rates of untreated poultry litter, four rates of ammonium nitrate, and an unfertilized control. Poultry litter and ammonium nitrate were surface-applied in April or May each year. Application rates of litter were 2.24, 4.49, 6.72, and 8.96 Mg ha^{-1} (1, 2, 3, and 4 tons acre^{-1}). Ammonium nitrate rates were 65, 130, 195, and 260 kg N ha^{-1} , and were based on the amount of total N applied during Year 1 with alum-treated litter. The study utilized a randomized block design with four replications per treatment.

Ten soil cores (0 to 5 cm) were taken from each of the 52 plots before the study, composited, and analyzed for Mehlich III P (Mehlich, 1984) and water-extractable P (Self-Davis et al., 2000). The treatments were then randomized so that the average Mehlich III P level for each treatment was within 1 mg P kg^{-1} to the overall average of 131 mg P kg^{-1} . Ten cores were also taken periodically (at least one time per year) for the duration of the study in a similar fashion and analyzed for Mehlich III P (Mehlich, 1984) and water-extractable P (WEP) (Self-Davis et al., 2000). The holes formed due to soil sampling were filled with soil cores taken from an area adjacent to each plot.

During Year 7 (April 2002) four 50-cm soil cores also were taken from each plot and were sectioned into the following

depths: 0 to 5, 5 to 10, 10 to 20, 20 to 30, 30 to 40, and 40 to 50 cm. These samples were analyzed for Mehlich III P and WEP, as described above. Total P in soil was also analyzed using ICP after digestion with a mixture of nitric and perchloric acid (Olsen and Sommers, 1982).

Alum-treated and normal poultry litter that were used in this study were obtained from six commercial broiler houses located in northwest Arkansas which are being used to study the effects of alum on NH_3 volatilization and poultry production (Moore et al., 1999, 2000). Al⁺Clear (poultry-grade alum manufactured by General Chemical Corporation) has been applied to three of the houses at a rate of $1816 \text{ kg house}^{-1}$ after each growout since 1994 and mixed into the litter using a litter “de-caker.” Chemical characteristics of the untreated and alum-treated litter used in this study for Year 1 are given in Moore et al. (1998).

To measure nutrient content and yields of tall fescue, a 1-m^2 area of each plot was periodically cut to a height of 10 cm with a bagger-mower (typically 3 or 4 times per year, depending on rainfall). All plots were harvested at the same time and all plant biomass was removed from the plots. During Year 6 of the study we began to have problems with moles burrowing through the plots. During this time, some soil contamination of the plant tissue was observed via the presence of elevated concentrations of titanium in the plant samples (Cherney and Robinson, 1983). To avoid soil contamination, subsamples for nutrient analysis were clipped by hand thereafter. For total P analysis of plant tissue, 0.5 g of dried, ground plant material was digested in nitric acid and analyzed using ICP.

Statistical analyses of the data were performed using SAS (SAS Institute, 1985). Significant differences between means were evaluated using Fisher's Protected LSD with alpha set at 0.05. The relationship between soil test P (either Mehlich III P or WEP) and time was modeled using simple linear regression.

Paired Watershed Study

The paired watershed study was conducted at the commercial broiler/beef farm described by Moore et al. (2000). Two identical watersheds that were 0.405 ha (1 acre) in size were constructed side by side on a hillside on a Captina silt loam soil with an average slope of 8%. The area where these watersheds were constructed had a history of poultry litter application and heavy cattle grazing. The watersheds were formed by building earthen berms and were equipped with flumes and automatic water samplers (American Sigma, Medina, NY). Barbed-wire fences were built around the watersheds to keep cattle out from 1994 through 2002. Since that time cattle have been allowed to graze the watersheds.

Poultry litter was surface-applied to each watershed in the spring (April or May) of each year using a commercial litter spreading truck (alum-treated litter was used on one side; normal litter on the other). Litter application rates (on an as-is basis) were 5.6 Mg ha^{-1} ($2.5 \text{ tons acre}^{-1}$) in 1995; 8.96 Mg ha^{-1} (4 tons acre^{-1}) in 1996 and 1997; and 5.6 Mg ha^{-1} from 1998 through 2005. The forage (mainly tall fescue) on the paired watersheds was either hayed or mowed for the first 8 yr of the study and was grazed thereafter.

The automatic water samplers were checked after every significant rainfall event ($>1 \text{ cm}$) within 24 h to determine if runoff had occurred. When a runoff event occurred, the flow data from the water sampler was downloaded and runoff samples were returned to the lab. During Year 1, the water samples were analyzed for pH, electrical conductivity, soluble reactive P (SRP), soluble metals, $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, soluble organic C, total P (TP), total metals, total N, and total C (see

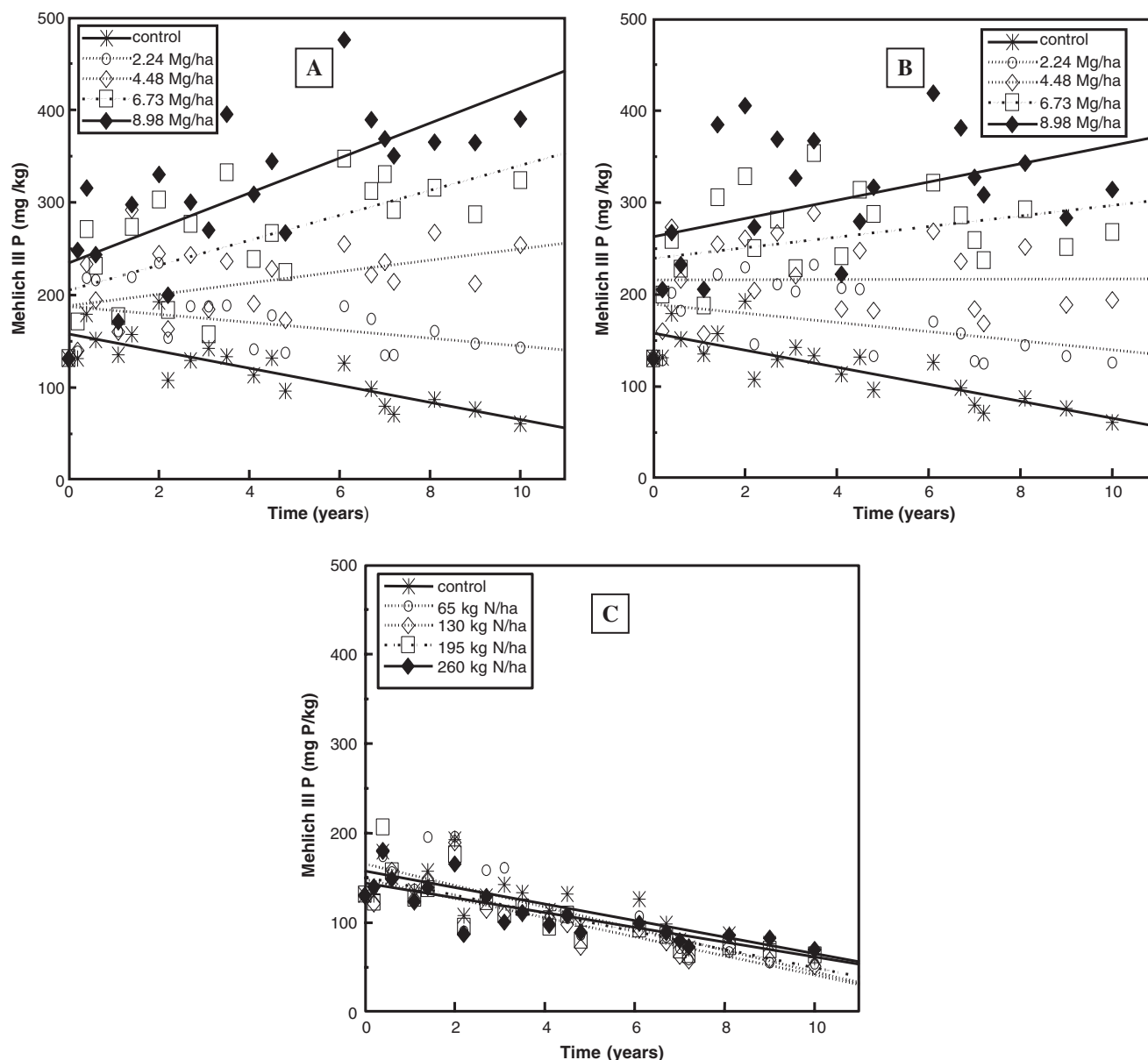


Fig. 1. Mehlich III P (0 to 5 cm) as a function of time for various rates of (A) alum-treated litter, (B) normal poultry litter, and (C) ammonium nitrate.

Moore et al., 2000). Since Year 1, water samples have been analyzed for SRP and TP. Samples for SRP were filtered through 0.45-um filter papers, acidified to pH 2 with HCl before being frozen, and analyzed using the ascorbic acid tech-

nique with an auto-analyzer according to APHA method 424-G (APHA, 1992). Unfiltered (acidified) samples were used for total P analysis. Statistical analyses of the watershed data were conducted using simple linear regression.

Table 1. Regression equations for the relationship between Mehlich III-extractable P in soil (0- to 5-cm depth) and time (years) for the three fertilizer sources.

Source	Rate	Equation	Regression coefficient (R^2)
Control	0 Mg ha ⁻¹	$y = -9.25x + 158$	0.67
Alum-treated litter	2.24 Mg ha ⁻¹	$y = -4.28x + 188$	0.17
Alum-treated litter	4.48 Mg ha ⁻¹	$y = 6.15x + 188$	0.19
Alum-treated litter	6.72 Mg ha ⁻¹	$y = 13.5x + 205$	0.42
Alum-treated litter	8.96 Mg ha ⁻¹	$y = 18.9x + 234$	0.50
Normal litter	2.24 Mg ha ⁻¹	$y = -4.97x + 190$	0.15
Normal litter	4.48 Mg ha ⁻¹	$y = 0.11x + 215$	0.00006
Normal litter	6.72 Mg ha ⁻¹	$y = 5.74x + 239$	0.12
Normal litter	8.96 Mg ha ⁻¹	$y = 9.90x + 262$	0.17
Ammonium nitrate	65 kg N ha ⁻¹	$y = -12.1x + 165$	0.68
Ammonium nitrate	130 kg N ha ⁻¹	$y = -10.7x + 148$	0.69
Ammonium nitrate	195 kg N ha ⁻¹	$y = -10.1x + 151$	0.67
Ammonium nitrate	260 kg N ha ⁻¹	$y = -8.26x + 114$	0.68

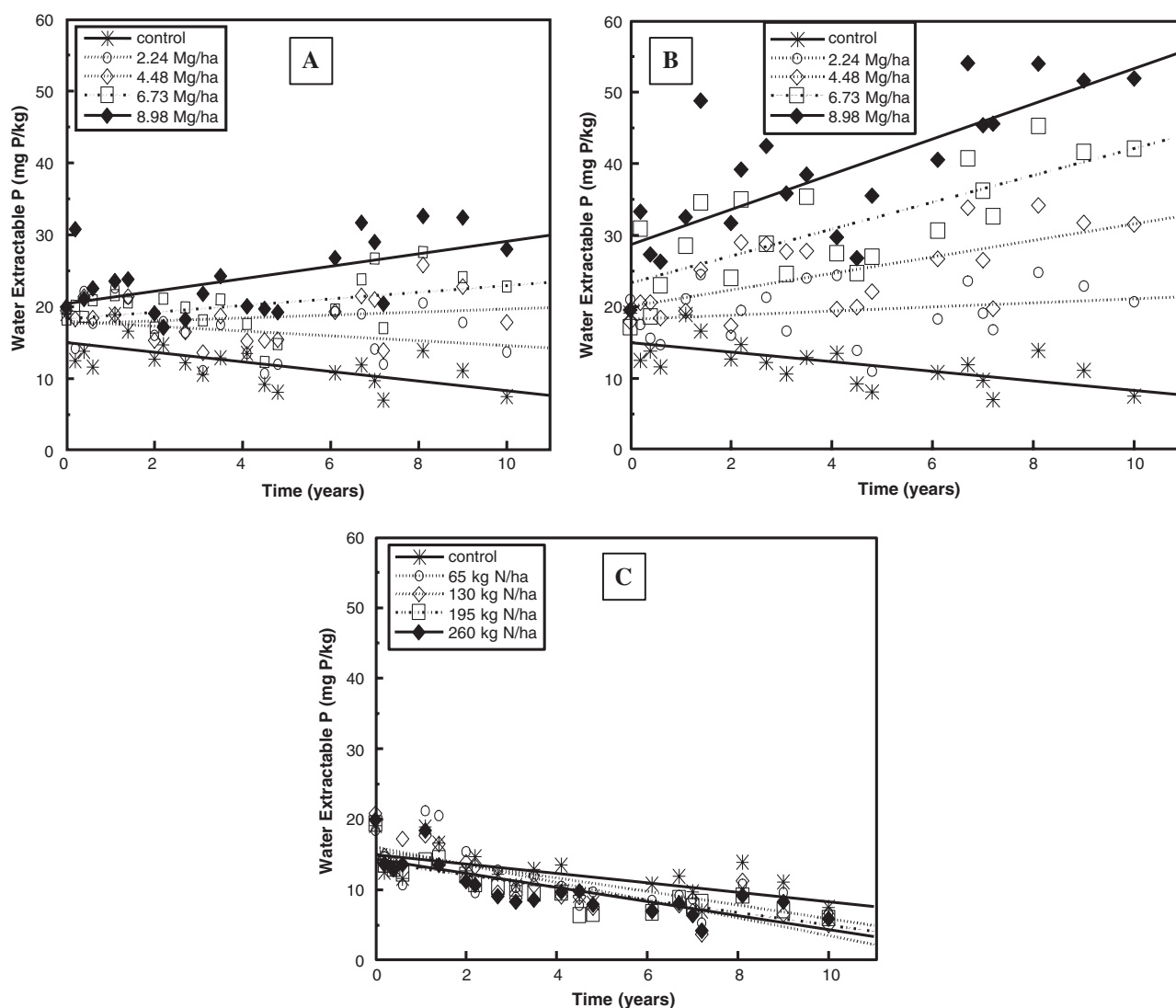


Fig. 2. Water-extractable P (0 to 5 cm) as a function of time for various rates of (A) alum-treated litter, (B) normal poultry litter, and (C) ammonium nitrate.

RESULTS AND DISCUSSION

Small Plot Study

Mehlich III P tended to increase over time if poultry litter applications were at 4.48 Mg ha^{-1} (2 tons acre^{-1}) or above, whereas at lower rates it tended to decrease (Fig. 1A, 1B, Table 1). In contrast, ammonium nitrate

applications resulted in reductions of Mehlich III P at all rates (Fig. 1C).

The gradual increase in Mehlich III P over time with the litter treatments is remarkable. The poultry litter utilized in this study had an average total P content of 1.5%. At an application rate of 4.48 Mg ha^{-1} approximately 67 kg P ha^{-1} would be applied each year, hence,

Table 2. Regression equations for the relationship between water-extractable P in soil (0- to 5-cm depth) and time (years) for the three fertilizer sources.

Source	Rate	Equation	Regression coefficient (R^2)
Control	0 Mg ha^{-1}	$y = -0.67x + 15$	0.40
Alum-treated litter	2.24 Mg ha^{-1}	$y = 0.34x + 0.18$	0.08
Alum-treated litter	4.48 Mg ha^{-1}	$y = 0.21x + 17.6$	0.04
Alum-treated litter	6.72 Mg ha^{-1}	$y = 0.46x + 18.3$	0.15
Alum-treated litter	8.96 Mg ha^{-1}	$y = 0.86x + 20.4$	0.28
Normal litter	2.24 Mg ha^{-1}	$y = 0.29x + 18.3$	0.05
Normal litter	4.48 Mg ha^{-1}	$y = 1.15x + 20.0$	0.41
Normal litter	6.72 Mg ha^{-1}	$y = 1.88x + 23.3$	0.56
Normal litter	8.96 Mg ha^{-1}	$y = 2.46x + 28.6$	0.57
Ammonium nitrate	65 kg N ha^{-1}	$y = -0.97x + 15.6$	0.49
Ammonium nitrate	130 kg N ha^{-1}	$y = -1.25x + 16.0$	0.70
Ammonium nitrate	195 kg N ha^{-1}	$y = -0.89x + 13.9$	0.66
Ammonium nitrate	260 kg N ha^{-1}	$y = -1.00x + 14.3$	0.62

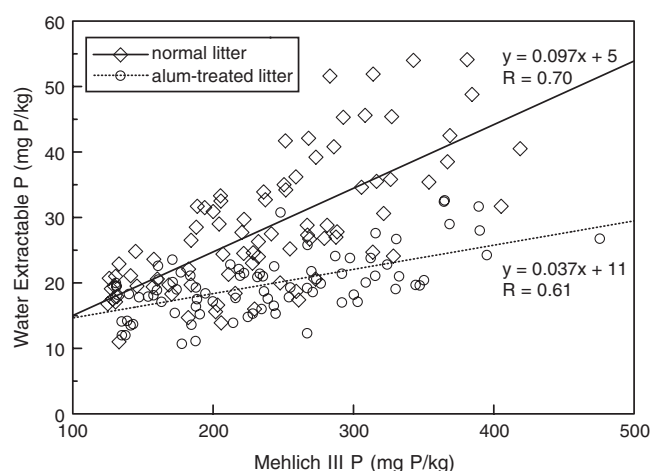


Fig. 3. Relationship between water-extractable P and Mehlich III P in soils fertilized with normal or alum-treated poultry litter.

over a 10-yr period, 672 kg P ha⁻¹ were applied. Assuming all applied P stayed in the top 15 cm of soil, then the total P would be expected to increase by roughly 300 mg kg⁻¹, yet Mehlich III P stayed the same at this rate. The reason Mehlich III did not increase at the lower application rates is likely due to P removal in harvested forage. These plots were managed similarly to a hayed pasture (forage was cut with a bagger mower and all clippings were removed). Fescue yields were roughly 5 Mg ha⁻¹ for plots receiving 4.48 Mg litter ha⁻¹ (Moore and Edwards, 2005). Assuming P concentrations in fescue averaged 4000 mg P kg⁻¹ during this time, then

the amount of P removed with the forage would be 20 kg P ha⁻¹ yr⁻¹ or 200 kg P ha⁻¹ over the 10-yr period. Hence, about two-thirds of the P was removed at this rate. Under a grazed system, the soil test P levels would probably be greater for all treatments, since most (~80%) of the P in grass consumed by cattle would be returned to the soil surface as manure.

Water-extractable P in soils fertilized with alum-treated litter remained relatively constant or decreased when alum-treated litter was applied at rates ≤ 6.72 Mg ha⁻¹ (Fig. 2A, Table 2). In contrast, WEP values increased in soils fertilized with normal litter at rates as low as 4.48 Mg ha⁻¹ (Fig. 2B, Table 1). Water-extractable P decreased with time with all rates of ammonium nitrate, as would be expected (Fig. 2C, Table 2). These results indicate that reducing soluble P in poultry litter with alum has a long-term effect on WEP in the soil.

Shreve et al. (1996) showed that alum additions to poultry litter resulted in lower WEP in soil than normal litter or litter amended with calcium hydroxide. They also evaluated the effects of various amended litters on P solubility in soil at pH 4, 5, 6, 7, 8 and the native pH (5.5). The lowest P solubility was noted with alum-treated litter at the pH extremes (4 and 8). These data fit the general paradigm of aluminum phosphate availability (i.e., P from these minerals would be more available in the pH range of 6 to 7). They also provide evidence that aluminum phosphate stability may not be affected by changes in farming practices or environmental conditions that change soil pH. Moore and Edwards (2005) showed that both alum-treated litter and normal litter increased soil pH.

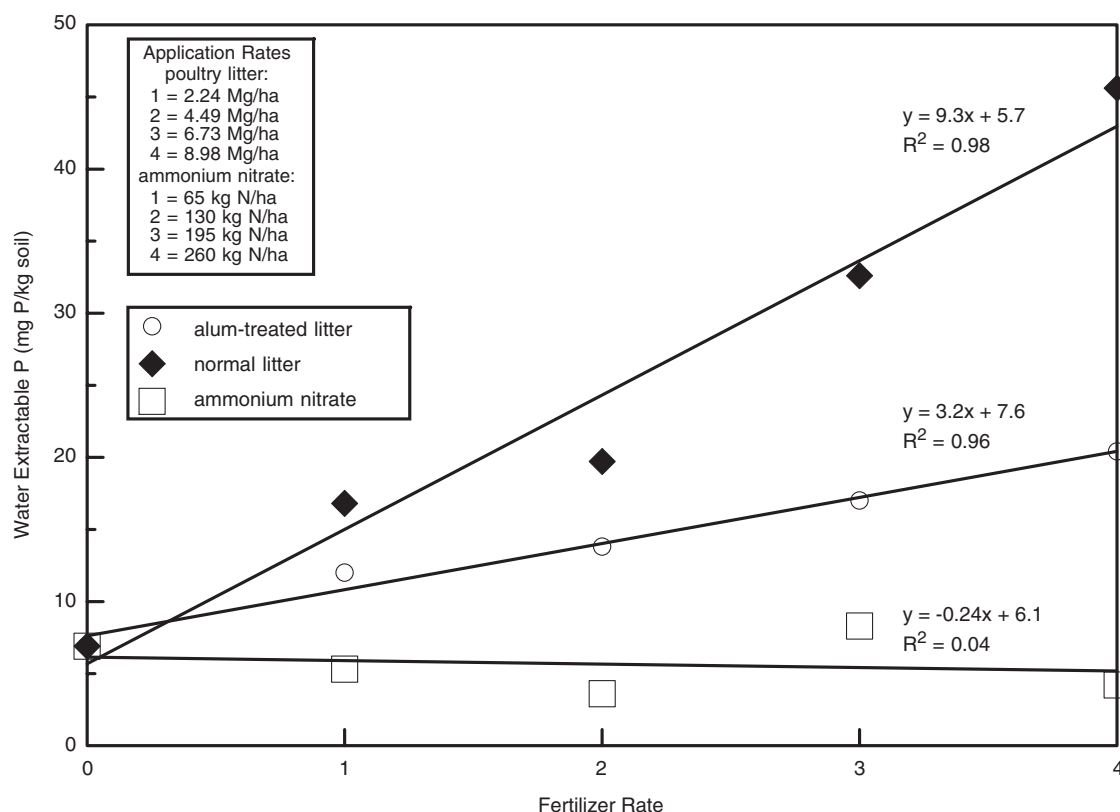


Fig. 4. Water-extractable P (0 to 5 cm) in soil as a function of fertilizer application rate after 7 yr of fertilization (LSD_{0.05} = 4.7).

The relationship between WEP and Mehlich III P is shown in Fig. 3. The slope of the line for normal litter is greater than that for alum-treated litter, indicating that for a given Mehlich III soil test P, there will be more soluble P (water-extractable P) in soils fertilized with normal litter compared to alum-treated litter. These data further indicate that the P associated with alum-treated litter is less soluble than that from normal litter. In agricultural systems with low erosion, soluble P is a primary source of P available for loss via runoff and/or leaching.

Although the data in Fig. 2 illustrate the effect of litter application rate on soluble P, it is difficult to make a direct comparison of the various fertilizer types on soluble P since the different treatments are not shown in the same graph. Hence, WEP data (0 to 5 cm) from one time (Year 7) were plotted as a function of fertilizer application rate (Fig. 4). These data show that when applied at the same rates, normal poultry litter resulted in roughly three times more soluble P than alum-treated litter. These results are expected, since alum additions to litter result in the formation of some type of aluminum phosphate mineral, which is believed to be relatively stable. In contrast, the concentration of Mehlich III-extractable P was found to be slightly greater in the surface soil of plots fertilized with alum-treated litter than normal litter in samples taken during Year 7 (Fig. 5).

We hypothesized that the reason Mehlich III P was greater in surface soils fertilized with alum-treated litter than with normal litter was that the P in normal litter

would be more apt to leach down the profile because it is more soluble. To test this hypothesis, soil samples were taken to a depth of 50 cm during Year 7. While Mehlich III P was slightly greater in the plots fertilized with alum-treated litter at the surface, it was greater with normal litter at the lower depths, indicating there was more downward P movement through the profile (leaching) with normal litter than alum-treated litter (Fig. 6). Further evidence of P leaching with normal litter was provided by the WEP levels, which were greater with normal litter to 30 cm (Fig. 7). The data shown in Fig. 6 and 7 were from the highest litter rates (8.96 Mg ha^{-1}). All other rates except the lowest rate behaved in a similar fashion (Tables 3 and 4).

The effect of the various fertilizer treatments on P leaching is best illustrated by the water-extractable P data from the 10- to 20-cm soil depth (Fig. 8). These data indicate that P solubility in soil either stayed the same or decreased slightly at the 10- to 20-cm depth as application rate increased for both alum-treated litter and ammonium nitrate. We believe this is due to increased P uptake by fescue at the greater fertilizer rates (due to greater N availability). In contrast, P solubility increased exponentially as the rate of normal poultry litter increased. The average WEP at the 10- to 20-cm depth was 288% greater for normal litter than alum-treated litter (9.08 vs. $3.15 \text{ mg P kg}^{-1}$). These data provide conclusive evidence that the addition of alum to litter reduces P leaching. Mehlich III P at the 10- to 20-cm depth followed similar trends, although the relationship was not an exponential increase (Table 4).

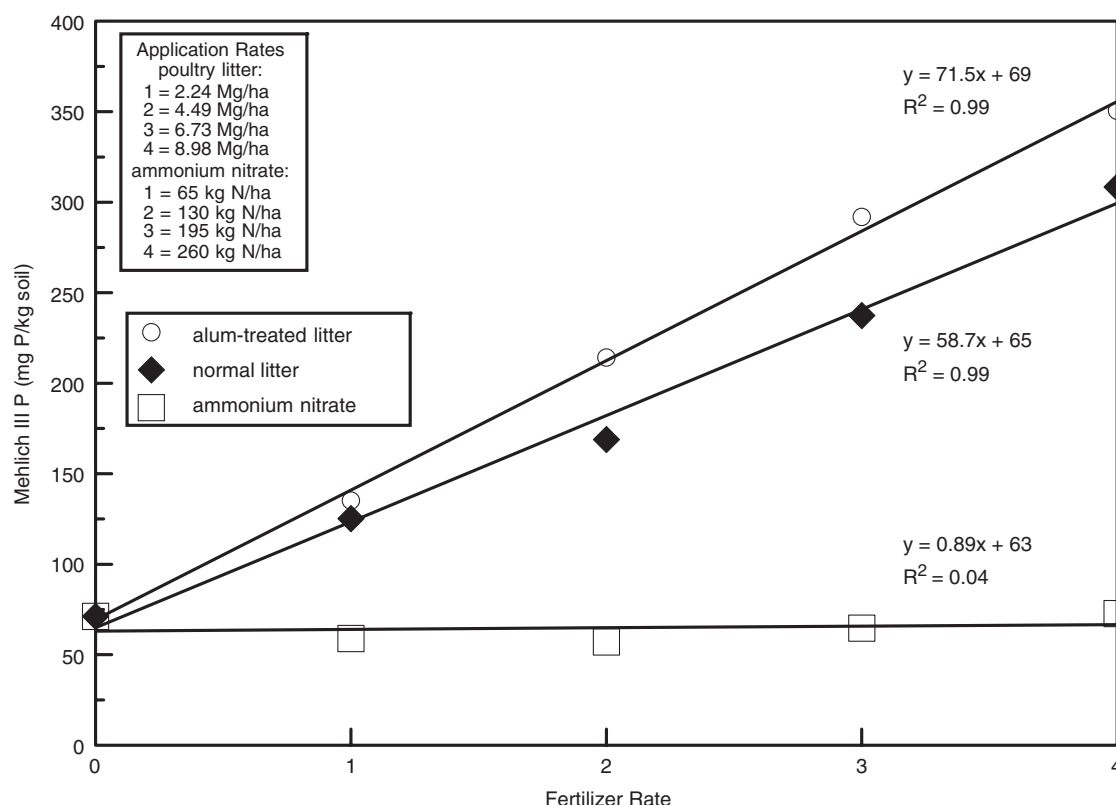


Fig. 5. Mehlich III-extractable P (0 to 5 cm) in soil as a function of fertilizer application rate after 7 yr of fertilization ($\text{LSD}_{0.05} = 47.3$).

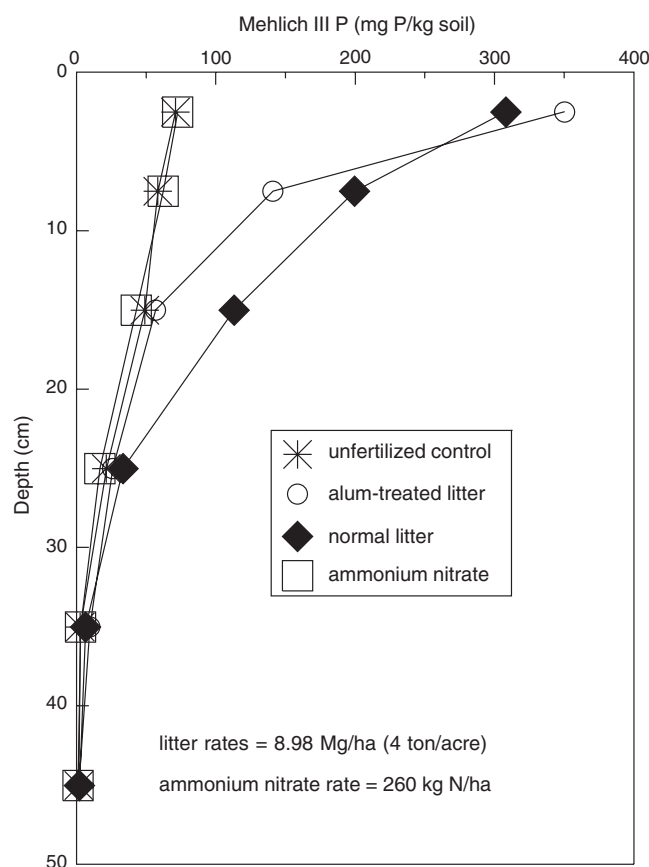


Fig. 6. Mehlich III P in soil as a function of depth after 7 yr of fertilization with the high rates of litter and ammonium nitrate.

Total P accumulation in soil followed the same trends as Mehlich III P (Table 5); that is, there was more downward movement of TP in plots fertilized with normal litter than alum-treated litter. The results of this study have broad implications for other areas where poultry litter application to agricultural soils is of concern. In the area surrounding the study site (Ozark Plateau), most poultry farms are located on land with silt loam soils. Many of these soils have a relatively high clay content at depths below 10 to 15 cm. The clay, which has a high Al and Fe

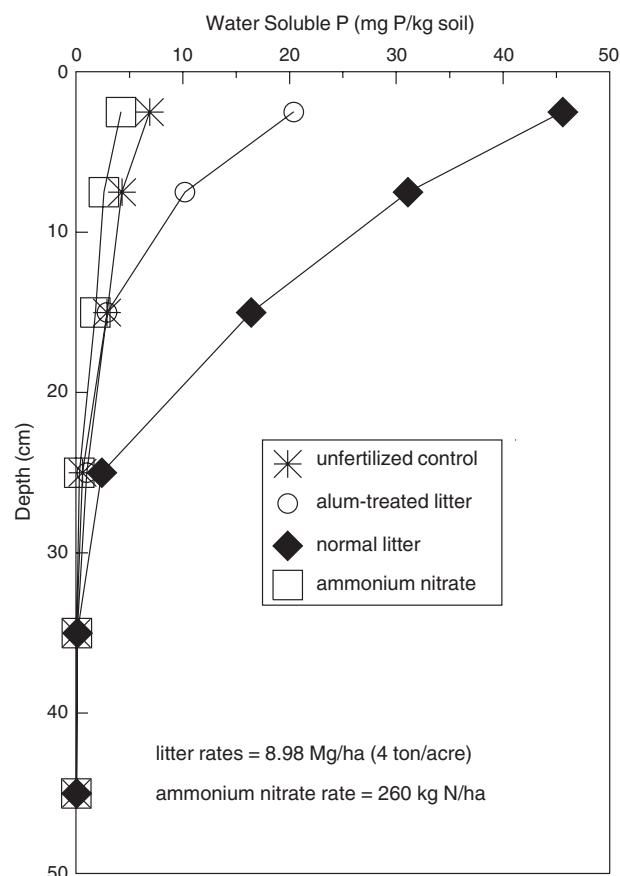


Fig. 7. Water-soluble P in soil as a function of depth after 7 yr of fertilization with the high rates of litter and ammonium nitrate.

content, gives the soil a high P sorption capacity with depth. Some poultry producing areas, such as the Delmarva Peninsula (Delaware-Maryland-Virginia) and Sand Mountain region (Alabama), possess extensive sandy soils where low P sorption capacities predominate. Under sandy conditions, P leaching is often a greater water quality concern than P runoff. Data from the current study provide strong evidence that alum additions to litter will reduce P leaching as well as P runoff.

Table 3. Effect of fertilizer treatment on water-extractable P contents in soil at various depths after 7 yr. Different letters within a column indicate significant differences in WEP within that soil depth.

Treatment	Depth 0–5 cm	Depth 5–10 cm	Depth 10–20 cm	Depth 20–30 cm	Depth 30–40 cm	Depth 40–50 cm
	mg P kg ⁻¹					
Unfertilized control	6.94efg	4.25fg	2.92d	0.56b	0.028b	0.028b
Alum-treated litter						
2.24 Mg ha ⁻¹	12.0def	6.55ef	3.76cd	1.42ab	0.100b	0.025b
4.48 Mg ha ⁻¹	13.8cde	5.99efg	3.03d	0.45b	0.043b	0.060a
6.72 Mg ha ⁻¹	16.9cd	7.39def	2.88d	0.86b	0.073b	0.020b
8.96 Mg ha ⁻¹	20.4c	10.2d	2.94d	1.02b	0.100b	0.025b
Normal litter						
2.24 Mg ha ⁻¹	16.8cd	9.23de	3.27d	0.61b	0.058b	0.020b
4.48 Mg ha ⁻¹	19.7c	14.8c	5.86c	0.98b	0.075b	0.043ab
6.72 Mg ha ⁻¹	32.7b	20.9b	10.7b	1.17ab	0.090b	0.030ab
8.96 Mg ha ⁻¹	45.6a	31.1a	16.4a	2.38a	0.115ab	0.035ab
Ammonium nitrate						
65 kg N ha ⁻¹	5.31fg	3.97fg	3.42d	0.54b	0.083b	0.043ab
130 kg N ha ⁻¹	3.65g	2.47g	2.28d	0.75b	0.223a	0.033ab
195 kg N ha ⁻¹	8.34efg	2.59g	2.78d	0.26b	0.055b	0.023b
260 kg N ha ⁻¹	4.19g	2.59g	1.81d	0.30b	0.065b	0.015b
LSD 0.05	6.93	3.63	2.16	1.35	0.122	0.032

Table 4. Effect of fertilizer treatment on Mehlich III-extractable P contents in soil at various depths after 7 yr. Different letters within a column indicate significant differences in Mehlich III P within that soil depth.

Treatment	Depth 0–5 cm	Depth 5–10 cm	Depth 10–20 cm	Depth 20–30 cm	Depth 30–40 cm	Depth 40–50 cm
	mg P kg ⁻¹					
Unfertilized control	71.1f	58.5ef	49.1de	21.5ab	2.70c	1.69ab
Alum-treated litter						
2.24 Mg ha ⁻¹	135.1de	83.4e	62.9cd	28.9ab	6.98abc	2.06ab
4.48 Mg ha ⁻¹	214.1c	85.1de	50.5de	20.7ab	4.04bc	2.25ab
6.72 Mg ha ⁻¹	291.8b	112.3cd	59.4cde	26.5ab	6.86abc	2.06ab
8.96 Mg ha ⁻¹	350.4a	141.0bc	56.8cde	26.1ab	9.83a	1.92ab
Normal litter						
2.24 Mg ha ⁻¹	125.1e	84.8de	49.1de	19.6ab	3.91bc	1.98ab
4.48 Mg ha ⁻¹	168.8d	122.7c	72.9bc	22.7ab	4.30abc	2.26ab
6.72 Mg ha ⁻¹	237.3c	159.3b	87.4b	26.8ab	4.62abc	1.95ab
8.96 Mg ha ⁻¹	308.3b	199.7a	113.2a	33.5a	6.53abc	2.18ab
Ammonium nitrate						
65 kg N ha ⁻¹	58.9f	58.4ef	54.5de	18.5ab	5.18abc	1.81ab
130 kg N ha ⁻¹	57.0f	51.9f	45.6de	16.4b	9.36ab	2.32a
195 kg N ha ⁻¹	64.6f	61.5ef	55.1cde	13.0b	3.38c	1.81ab
260 kg N ha ⁻¹	72.7f	62.2ef	43.0e	16.9ab	3.02c	1.19b
LSD 0.05	36.4	28.6	18.0	17.1	5.72	1.08

Forage P contents for Year 7 are shown in Fig. 9. Plants fertilized with normal poultry litter had the highest forage P contents; plants fertilized with alum-treated litter had intermediate P content, and plants receiving ammonium nitrate had the lowest P content (Fig. 9). The critical concentration of P in tall fescue for P deficiency is around 0.2% or 2000 mg kg⁻¹ (Olsen's Agricultural Laboratory, 1997). On two occasions (last harvest of Year 6 and last harvest of Year 8) the fescue grown with the highest rate of ammonium nitrate (260 kg N ha⁻¹) had P concentrations below this critical value (data not shown). Between Years 6 and 9 the Mehlich III P con-

centration of the plots receiving the high rate of ammonium nitrate varied between 66 and 100 mg P kg⁻¹ in the top 5 cm, well in excess of the agronomic threshold of 50 mg kg⁻¹ identified by University of Arkansas Cooperative Extension guidelines (N. Slaton, personal communication, 2006). We hypothesize that the high Al present in the soils fertilized with ammonium nitrate (Moore and Edwards, 2005) interfered with P availability, uptake, and/or translocation within the plant.

Although the forage P concentrations tended to be lower with alum-treated litter than normal litter, there was no significant difference in P uptake by fescue be-

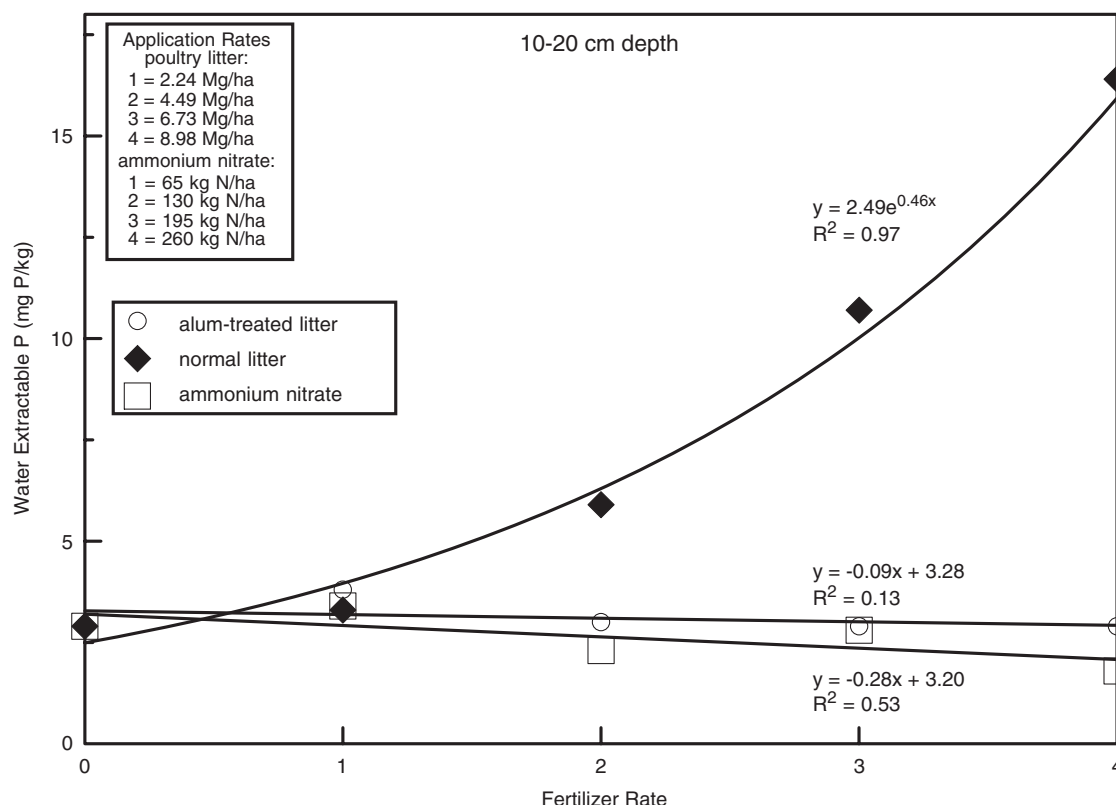


Fig. 8. Water-extractable P in soil at the 10- to 20-cm depth as a function of fertilizer application rate after 7 yr of fertilization (LSD_{0.05} = 2.1).

Table 5. Effect of fertilizer treatment on total P contents in soil at various depths after 7 yr. Different letters within a column indicate significant differences in total P within that soil depth.

Treatment	Depth 0–5 cm	Depth 5–10 cm	Depth 10–20 cm	Depth 20–30 cm	Depth 30–40 cm	Depth 40–50 cm
	mg P kg ⁻¹					
Unfertilized control	540fg	486de	394c	303a	194bcd	172a
Alum-treated litter						
2.24 Mg ha ⁻¹	761de	514de	428bc	314a	202abcd	174a
4.48 Mg ha ⁻¹	865cd	538cde	420bc	268a	174d	174a
6.72 Mg ha ⁻¹	1098a	621bc	417bc	298a	215abc	171a
8.96 Mg ha ⁻¹	1124a	626bc	399bc	302a	238a	168a
Normal litter						
2.24 Mg ha ⁻¹	639ef	508de	410bc	285a	217abc	161a
4.48 Mg ha ⁻¹	747de	551cd	452abc	267a	190bcd	173a
6.72 Mg ha ⁻¹	932bc	724a	468ab	323a	187bcd	160a
8.96 Mg ha ⁻¹	1052ab	705ab	526a	331a	199abcd	165a
Ammonium nitrate						
65 kg N ha ⁻¹	482g	481de	416bc	254a	182cd	168a
130 kg N ha ⁻¹	507g	464de	393c	277a	223ab	168a
195 kg N ha ⁻¹	514fg	459de	414bc	262a	185cd	176a
260 kg N ha ⁻¹	546fg	452e	384c	289a	191bcd	162a
LSD 0.05	125	96	74	91	41	25

tween these two treatments (Fig. 10) due to the greater biomass production by fescue fertilized with alum-treated litter. Shreve et al. (1995) and Moore and Edwards (2005) found forage yields were greater with alum-treated litter than normal litter. These yield increases with alum are a result of increased N content in the litter due to reduced NH₃ volatilization (Moore et al., 1995, 1996, 1999, 2000). The additional N in alum-treated litter is in the form of ammonium (Moore et al., 1995, 1996), which more available for plant growth than organic forms of N.

One concern over the treatment of poultry litter with alum has been its possible effect on P availability to

crops. The data from Fig. 10 indicate that there is little to no long-term effect of alum on P availability to tall fescue when compared to normal poultry litter. With normal poultry litter there is excess P applied relative to the N application rate (N/P ratio is typically 2:1). Crops have an N/P ratio of around 8:1. Treating litter with alum binds much of this excess P into nonavailable forms. Moore et al. (2000) showed alum additions to litter reduced P runoff by 75%. If alum reduces the plant available P by 75% as well, then the “effective” N/P ratio would increase from 2:1 to roughly 2 to 0.25 (or 8:1); which is what most crops need. Hence, alum-treatment of ma-

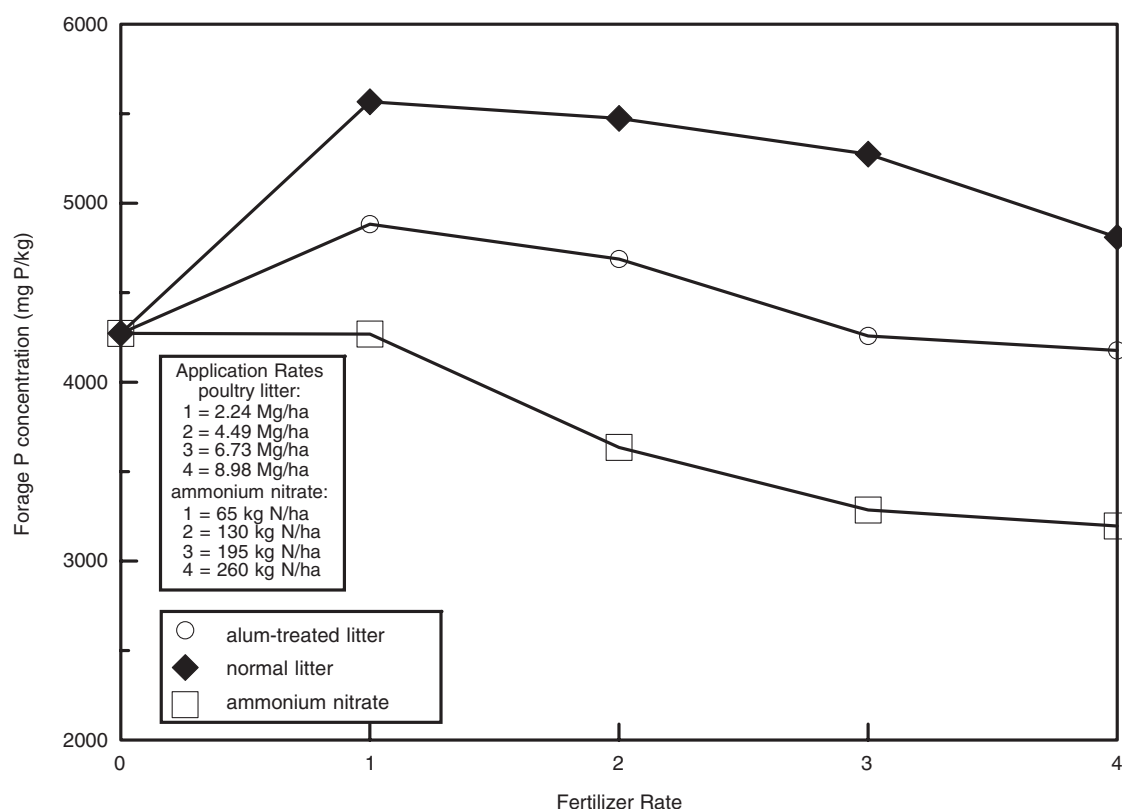


Fig. 9. Average forage P concentration during Year 7 as a function of fertilizer rate (LSD_{0.05} = 591).

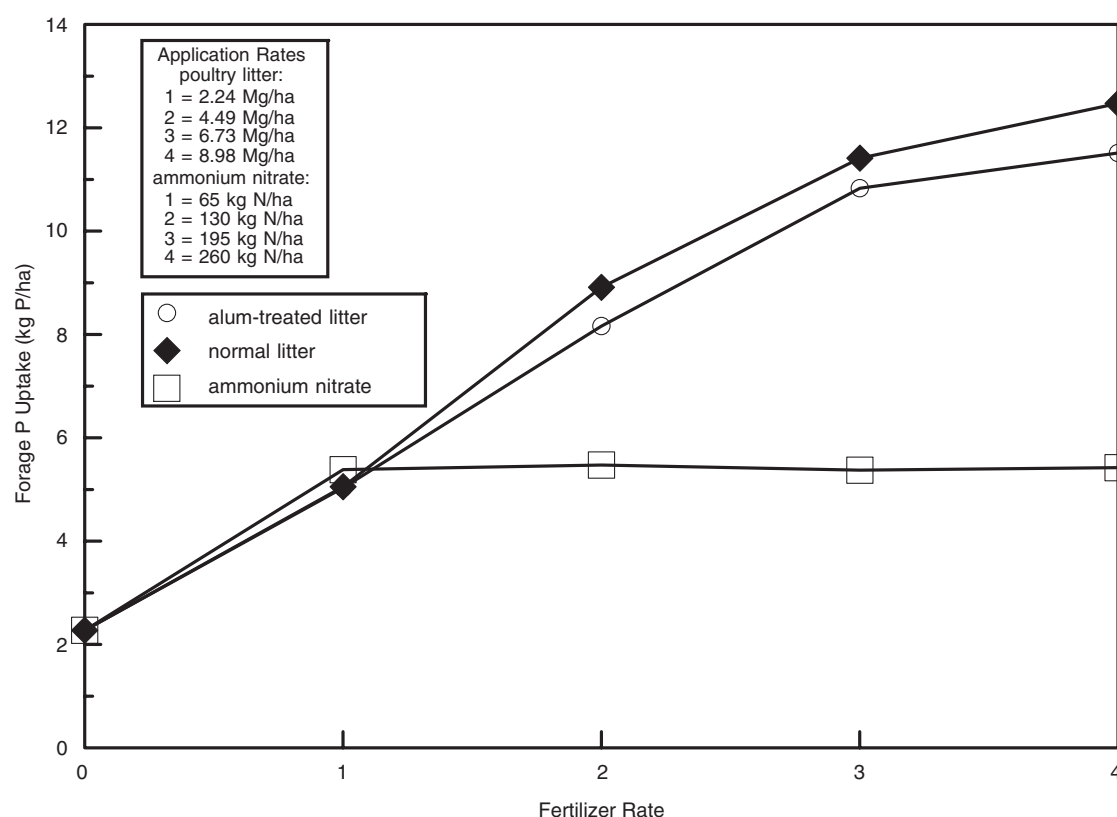


Fig. 10. Average P uptake by tall fescue during Year 7 as a function of fertilizer rate ($LSD_{0.05} = 3.8$).

nure is a way of modifying a fertilizer so that its chemical composition more closely fits the needs of the plant.

Paired Watershed Study

Runoff data from the two watersheds are shown in Table 6, as well as in Fig. 11 and 12. The average runoff volume over the 10-yr period was similar from both watersheds; however, the P concentration of the watershed fertilized with normal litter was greater than that with alum-treated litter (5.15 mg P L^{-1} vs. 1.68 mg P L^{-1} , respectively). This resulted in a substantial difference in P loads in runoff. The average P load was $0.45 \text{ kg P ha}^{-1}$ for alum-treated litter and $1.50 \text{ kg P ha}^{-1}$ for normal litter.

Cumulative P loads in runoff from normal litter were 340% greater than that from alum-treated litter over the 10-yr period (15.0 vs. $4.45 \text{ kg P ha}^{-1}$) (Fig. 11).

The list of best management practices (BMPs) that can be used for reducing P in runoff has grown over the past few years. Practices such as buffer strips, constructed wetlands, diet modification, pasture renovation, fencing cattle from streams, growing crops that reduce surface runoff, and utilizing the P index to write nutrient management plans all have been shown to reduce P in runoff (Chaubey et al., 1995; Braskerud, 2002; Self-Davis et al., 2003; DeLaune et al., 2004a, 2004b; Maguire et al., 2005). However, none of these reduce P runoff as much as alum.

Table 6. Runoff water volumes, P concentrations, and P loads from paired watersheds over a 10-yr period.

Year	Alum-treated litter			Normal litter		
	Runoff volume	P Conc.	P Load	Runoff volume	P Conc.	P Load
	L ha^{-1}	mg P L^{-1}	kg ha^{-1}	L ha^{-1}	mg P L^{-1}	kg ha^{-1}
0	1558	0.13	0.0002	3449	0.14	0.0005
1	380 316	1.46	0.55	787 923	4.04	3.18
2	122 222	2.18	0.27	165 501	8.84	1.46
3	328 010	1.93	0.63	282 346	8.04	2.27
4	0	—	0	0	—	0
5	323 551	1.25	0.40	321 040	3.37	1.08
6	233 642	1.89	0.44	233 642	6.97	1.63
7	655 319	1.23	0.81	786 906	2.85	2.24
8	0	—	0	0	—	0
9	554 291	2.20	1.22	589 244	4.81	2.84
10	94 390	1.31	0.12	141 121	2.30	0.33
Average†	269 174	1.68	0.45	330 772	5.15	1.50
Standard deviation	211 539	0.39	0.36	278 896	2.33	1.09

† Average and standard deviation calculated on data from Years 1 through 10, since litter had not been applied during Year 0.

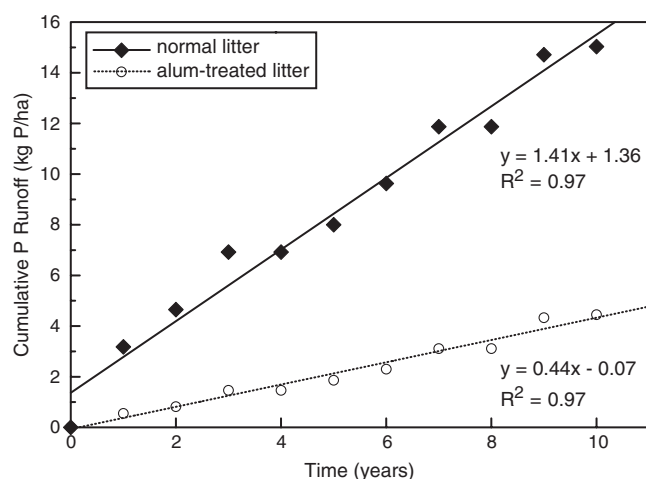


Fig. 11. Cumulative phosphorus loads in runoff from paired watersheds fertilized with alum-treated and normal litter.

As mentioned earlier, the slope, soil type, and vegetation of the paired watersheds was similar. Mehlich III-extractable P (0 to 15 cm) in both watersheds in this study was also identical (308 kg P ha⁻¹ initially and 560 kg P ha⁻¹ at Year 10), indicating soil test P had little or no effect on the differences observed in P runoff. Likewise, TP application rates from normal and alum-treated litter were very similar (data not shown). The only variable that is really different between these two watersheds is the amount of soluble P applied. To evaluate the effect of this variable, cumulative P loads in runoff were plotted as a function of the amount of cumulative soluble P applied (Fig. 12). The relationship shown between these two variables strongly indicates that the amount of soluble P applied is the critical variable in controlling P loss in runoff in pasture systems (i.e., one regression line explains the behavior of both treatments). Many different studies have shown that P runoff from pastures fertilized with manure is more closely related to the amount of soluble P applied than any other variable (Sharpley and Moyer, 2000; Kleinman et al., 2002a, 2002b; DeLaune et al., 2004a).

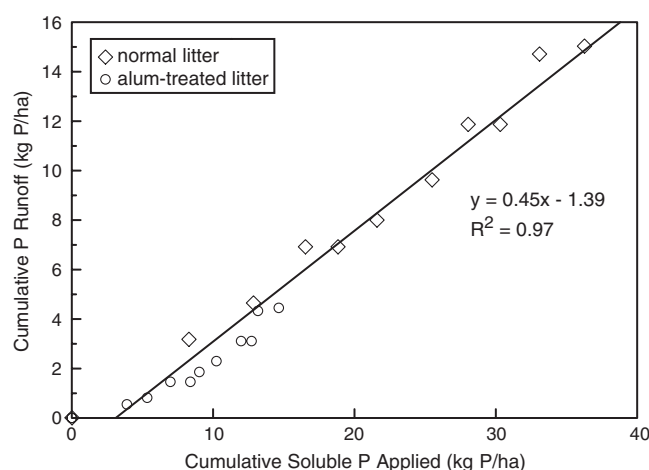


Fig. 12. Cumulative phosphorus loads in runoff from paired watersheds fertilized with alum-treated and normal litter as a function of the amount of cumulative soluble phosphorus applied.

CONCLUSIONS

Previous studies have shown that the addition of alum to poultry litter reduces P, heavy metal and hormone runoff, reduces NH₃ emissions to the atmosphere, reduces pathogens responsible for foodborne illness, results in greater crop yields, and has no negative effect on Al availability in soils, Al runoff, and/or Al uptake by plants. Lower NH₃ levels in chicken houses treated with alum result in heavier birds, improved feed conversion, lower mortality, and lower energy use (due to less ventilation) making this treatment cost-effective. The results of the long-term small plot study confirm that the P associated with alum-treated manure is less soluble in the soil than P derived from normal (untreated) litter. Soil samples taken after 7 yr of litter application reveal that P translocation down the profile is greater with normal litter than alum-treated litter. Therefore, alum significantly reduces P leaching in soils over the long term. Furthermore, P uptake by tall fescue was not affected by alum treatment. The cumulative P load over a 10-yr period from a watershed fertilized with normal litter was 340% greater than the P load from the watershed which received alum-treated litter. Cumulative P loads in runoff were highly correlated to the cumulative amount of soluble P applied, but were poorly correlated to total P applied or soil test P.

The results from this and other studies indicate that treatment of poultry litter with alum is not solely a short-term solution to the problem of nonpoint source P losses from agricultural lands. On the contrary, a large body of research now exists to support the conclusion that treating poultry litter with alum produces favorable environmental and agronomic results over short and long time periods. We argue that research showing alum to be cost-effective in improving soil, water, and air quality over the long term while also improving animal and crop production provides compelling evidence that alum treatment of poultry litter is a sustainable best management practice.

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